Hygro-thermo-mechanical properties of earthen materials for construction : a literature review

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HYGRO-THERMO-MECHANICAL PROPERTIES OF EARTHEN MATERIALS FOR CONSTRUCTION: A LITERATURE REVIEW

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Abstract:
Although earth has been used for construction for millennia and is still one of the most widely used building materials in the world, it is still difficult to find reliable values for the hygro-thermal and mechanical properties of earthen materials. Only little scientific research has been conducted on this material compared to the huge literature available concerning cementitious materials. Considering the literature available on earthen materials, a majority of studies deal with cement or lime stabilized earth for compressed earth blocks or rammed earth, and less has been done about natural unstabilized earth.

The only existing comprehensive overview on the hydro-thermal and mechanical properties of earthen materials was authored by CRAterre-ENSAG and published 25 years ago. Now, for the second time in its thirty years of existence, CRAterre-ENSAG has undertaken the task of re-actualizing this synthetic knowledge by writing a comprehensive review of the existing literature on the subject, thanks to the CRAterre laboratory documentation centre, which is the most complete source of information on earthen construction and architecture in the world (more than 20.000 references).

In the present work, we intend to compile the most reliable experimental data on the hygro-thermal and mechanical properties of natural earth. We will inventory the performances determined by several research teams for rammed earth, compressed earth blocks, adobe, cob and mortar. We will discuss the reliability of the experimental techniques used. We will provide an overview on the state of knowledge concerning the different properties as well as on the lacking data. Finally, this literature review will also give some orientations for further scientific research.

1 INTRODUCTION

Building with earth requires that artisans have a very good knowledge of the material. Yet, there is limited scientific knowledge of the material. While builders develop their knowledge on the field, through direct experience, engineering consulting firms are hampered by a lack of reliable data regarding the properties of earth. Norms and standards for earth construction are few, partial and often deal with CEBs, stabilized with cement.

However, there are many other reliable construction techniques involving earth materials that do not require the use of mineral stabilizers, as demonstrated through centuries-old examples such as the buildings, mosques and skyscrapers in the towns of Ghadames, Libya and Shibam in Yemen, the castle of Baños de la Encina in Andalusia, the Mosque of Djenne in Mali, some sections of the wall of China, the tulous, large residential complexes of the Hakka in China, or more locally the many farms built with earth around the Rhône-Alpes region in France (Fontaine and Anger, 2009). These examples clearly show that it is possible to use earth for the construction of sustainable buildings.

This report is an update on the knowledge available on the hygrometric, mechanical, and thermal properties of earth, 22 years after the publication of the book of Houben and Guillaud, 1989. It deals mainly with the intrinsic properties of the material. This update is an opportunity make an inventory of knowledge and highlight the technical data gaps that could be usefully filled.

Documents and information were made available through CRAterre's documentation centre and scientific journals. Only results for which the materials and experimental protocols are described at least briefly have been included ; this significantly reduces the number of documents that were used in this survey. In addition, we were interested in non-stabilized earth exclusively, which disqualified a great portion of the scientific data available.

2 DRY DENSITY

The dry density of soil is the ratio between its mass and its volume measured in the dry state, after oven dying at 105°C. This property dep ends on several parameters, dealing mainly with grain size distribution, the volume and nature of the binding phase, the water content involved in the implementation of the earth materials, and the energy involved in compaction in earth materials compacted for building purposes.

Taking into account the values found through different document sources, we suggest to distinguish two families of techniques for the implementation of earth, leading to different properties of the earth material when dry: implementation by compaction (rammed earth, CEBs) or plastic state implementation (adobe, wattle and daub, cob). To these two families, a third category can be added, involving the addition of a high proportion of plant fibers (straw-earth, hemp) into the earth mix, which leads to much lighter materials. Table 1 gives typical ranges of variation in terms of the clay content, plasticity index, initial water content and dry density for these three families (Azeredo, 2005, CSTB, 2007, Bahar, 2004, Barras, 2010, Bui, 2008, Degirmenci, 2008, Goodhew et al., 2000, Goodhew and Griffiths, 2005, Heath et al., 2009, Kleespies, 1994, Laurent et al., 1984, Laurent, 1987, Mueller and Simon, 2002, Vega et al., 2011, Morel et al., 2003, Ola, 1987, Hakimi et al., 1996, Hall and Djerbib, 2004, Jaquin et al., 2009, Kouakou and Morel, 2009, Maniatidis, 2008, Olivier, 1994, P'kla et al., 2003).

Technique	Clay content (%)	Plasticity Index (%)	Initial water content (%)	Dry density (kg/m3)
Compaction	5 - 30	5 - 30	5 – 15	1600 - 2200
Plastic moulding	20 - 40	15 - 35	15 – 35	1200 - 2100
With added fibres				300 - 1200

Tab. 1 – Typical values of dry density and other parameters for earthen materials.

3 HYGROMETRIC PROPERTIES

3.1 Water content

The water content of earth is a parameter of prime importance if we are interested in the mechanical and thermal properties of the material, so it is important to know the normal water content range of earth in ambient humidity. The water content of soil at equilibrium is higher if:

- relative humidity is high,
- ambient temperature is low,

- porosity is high,
- the accessible surface area of pores is important,
- the affinity of clay and water (and therefore the activity of clay) is high,
- the sample state results from dewetting from a previous higher moisture state.

In normal conditions of temperature and pressure, with a relative humidity below 70%, the water content percentage in earth walls generally varies between 0.5 and 5%. It can be higher especially in the presence of swelling clays and aggregates containing micropores and microroughness (Hall et al., 2009, Laurent, 1986, Hansen and Hansen, 2002, Heath et al., 2009, Maniatidis and Walker, 2008, Bourgès, 2003, Holl and Ziegert, 2002).

Eckermann et al. compared vapour absorption measurements on coatings of various kinds (Eckermann et al., 2007). Although the measurements were not performed at the equilibrium moisture content, they are helpful in making qualitative comparisons between the different samples tested. It appears from this study that earth generally has a greater capacity to bind water vapor than concrete or gypsum. This large water retention capacity is linked to the porous and microporous structure of soil, but also to the physico-chemical affinity between clay and water. Swelling clays are those that have the greatest affinity to water, due to their large surface area and high cation-exchange capacity.

3.2 Shrinkage and swelling

During the drying phase, the soil undergoes a volumetric contraction or shrinkage, due to the withdrawal of water: clay platelets tighten due to the increase of capillary forces caused by the loss of water as suction increases. This shrinkage may in certain circumstances cause cracking and so it must be controlled. Conversely, when a dry soil is loaded with moisture, it expands as a result of the relaxation of capillary pressure, and the swelling of clays having a high affinity for water.

For practical purposes, it is useful for builders to know the values of shrinkage of the soil from its current state to its implementation as a building material, which is not the saturated state.

The amplitude of shrinkage is limited if:

- the water content used in the implementation of the material is low,
- the surface area and cation exchange capacity of clays are small,
- the clay content is low,
- the porosity is high (the space between the grains is not filled with binding clay phase),
- the soil contains vegetal fibres: the addition of straw is an effective way to prevent or limit shrinkage.

The presence of salts in the soil can also alter the magnitude of shrinkage (Smith et al., 1985, Bourgès, 2003). The mechanisms involved are complex and dependent on the nature of the ions present.

The shrinkage of soil from its raw state to its implementation as a building material can vary between 1 and 20%. For rammed earth, the shrinkage percentage lies in the range of 1 to 3% (Robiquet, 1983, Gray anf Allbrook, 2002, Bourgès, 2003, Bouhicha et al., 2005, Smith et al., 1985, Heath et al., 2009, Walker and Stace, 1997, Bahar et al., 2004, Degirmenci, 2008, Hall et al., 2004, Kouakou and Morel, 2009, Maniatidis et al., 2007, P'kla et al., 2003, Vega et al., 2011).

3.3 Water vapour permeability

The permeability to water vapour in a building material allows to define its moisture exchange capacity between the inside and the outside of a building. The higher the permeability, the easier the exchange between outdoor air and indoor air. It is therefore an important property to consider regarding comfort inside the house.

For building materials, the factor of resistance to water vapour, μ, is used to characterize the permeability of a material to water vapour. It is equal to the ratio between the permeabilities of air and of the sample to water vapour. The higher the factor of resistance, the more difficult the moisture exchange between outdoor air and indoor air becomes.

For hygroscopic materials such as earth, which may fix a certain amount of air moisture, permeability increases with relative humidity. So the factor of resistance to water vapour μ decreases as the relative humidity increases. In theory, a single measure of permeability is not sufficient to fully characterize the hygrometric behaviour of earth.

For earth, μ varies between 5 and 13 and mainly depends on the pore size distribution, the nature of clays and their content. Earth has a permeability to water vapour equivalent to that of cellular concrete, lightweight aggregate concrete, gypsum and baked earth (Kleespies, 1994, CSTB, 2007, Utz, 2004, Bourgès, 2003, Hall et al., 2009, Volhard and Röhlen, 2009, NF EN 1745 :2002).

4 MECHANICAL PROPERTIES

4.1 Experimental precautions for the uniaxial compressive test

The main mechanical property of earth that is of interest to builders is its uniaxial compressive strength. To measure it, there are many available testing procedures which do not, unfortunately, lead to the same results for the same types of materials (Morel et al., 2007, Fontaine, 2004). In most cases, experimental conditions influence the results and it is not the intrinsic compressive strength of the material that is being measured. Thus, these values cannot be used in a comparative manner.

The following precautions must be taken in order to properly measure the uniaxial compressive strength of earth (Morel et al., 2007, P'kla, 2002, Walker, 2004, Olivier et al., 1997, Fontaine, 2004) :

- Choose sample dimensions greater than 5 times the size of larger particles.
- Choose an aspect ratio between 1.5 and 2.
- Obtain homogeneous samples.
- Let the samples stabilize in the desired hygrothermal conditions.
- Coat the samples with a material as rigid as earth (a fine earth mortar, for example) in order to obtain smooth and parallel surfaces.
- Use a ball joint above the top plate of the press if the surfaces are not perfectly parallel.
- Lubricate the contact between the sample and the press plates to reduce friction.

To measure the constitutive law and the elastic modulus of the specimens, care must be taken to measure the strain in the middle of the samples (using strain gauges for example) to avoid edge effects and the deformation caused by an anti-friction systems (Mollion, 2009).

4.2 Elastic modulus

Young's modulus for earth is difficult to measure from a compression test. Its determination requires a sufficiently precise local strain measurement. It is therefore very difficult to find written sources with reliable values of the elastic modulus of earth.

If surface roughness is imperfect, we can see a phase in which the curve increases progressively at the beginning of the testing, which corresponds to the crushing of surface ridges (Bui, 2008, Kouakou and Morel, 2009). This phase is not characteristic of the material and hides the elastic behavior of the original material.

To our knowledge, the only study that provides reliable measurements of the elastic modulus based on compression tests is that of Mollion, in which a measuring device adapted to strain measurement is used: three strain gauges placed around the sample measure the deformation in the middle third of the specimen (Mollion, 2009).

Other authors measure the elastic modulus using other techniques based on the measure of the resonance frequencies of specimens (Fontaine, 2004), or the speed of propagation of ultrasound (Bourgès, 2003).

According to data from these studies, Young's modulus for raw earth is between 1 and 5.5 GPa. It gets higher depending on how low the porosity and moisture content are, and on how high the clay content and specific surface area are. However, the relationship between the composition of the earth, its microstructure and its elastic modulus is not clearly established.

The recommended modulus values vary but always lie below 1 GPa (Walker, 2001, Walker et al., 2005, NZS 4297 :1998, Maniatidis and Walker, 2003). This modulus lacks a clear definition : how to measure it? Is the real Young's modulus of interest to builders, or do they just need an apparent modulus measured under certain conditions of stress?

4.3 Uniaxial compressive strength

Standards often require testing protocols that do not measure the intrinsic strength of the material: the measure is partly influenced by the test devices. This is due in part to the fact that testing procedures for earth materials are based on standard tests for cement concretes or fired clay bricks, while the mechanical properties of these materials are very different.

We have listed the most reliable results. The compressive strength of earth viable for construction can vary between 0.4 and 5 MPa. For rammed earth, the values are narrower: 0.5 to 3 MPa, the most common value being about 1.5 MPa (Azeredo, 2005, Barras, 2010, Bui, 2008, Bullen and Boyce, 1991, Fontaine, 2004, Hakimi et al., 1996, Jaquin et al., 2009, Kouakou and Morel, 2009, Maniatidis et al., 2007, Maniatidis and Walker, 2008, Mollion, 2009, Morel et al., 2003, Olivier, 1994, P’kla, 2002, P’kla et al., 2003).

The following parameters improve compressive strength : a high density, a low water content, a high clay and silt content, a high specific surface area of the clays, good homogeneity, small grains.

Based on the present state of knowledge, it is not possible to predict the compressive strength of a given soil without making experimental tests. Knowing the density, water content or clay content of earth is not enough. Many other parameters are involved in the mechanisms of cohesion of earth, which determine its strength. The relationship between the microstructure of earth and its macroscopic mechanical properties is very complex.

4.4 Tensile strength

Tensile strength, like shear strength (for which we could find no values in the scientific literature) are considered of minor importance as compared to compressive strength in the field of construction, because earth is stressed in compression. It can be measured by indirect tests such as split testing and the three point bending flexural test.

The few values identified show that earth has a tensile strength of about 0.1 to 0.5 MPa (Bahar et al., 2004, Hakimi et al., 1996, Jaquin et al., 2009, Morel et al., 2003, Olivier, 1994, P'kla et al., 2000, P'kla et al., 2003).

5 THERMAL PROPERTIES

5.1 Thermal inertia

Inertia is the ability to store heat and release it slowly. It allows to shift variations in temperature inside the house from the outside, and to cushion temperature changes. It depends primarily on the thermal mass of materials: the higher this capacity, the more the material may provide inertia to the building.

Another phenomenon may contribute to the thermal inertia of a wall: the latent inertia caused by the evaporation and condensation of water inside the wall. This property, specific to hygroscopic porous materials, such as earth, makes it a natural phase change material.

Heat capacity, c, is expressed in J/kg.K. It is connected to the volumetric heat capacity C in J/m3.K by the relation $C = c.\rho$, where ρ is the mass density of earth.

Earth's heat capacity c varies from 600 to 1000 J/kg.K with a mean value of 800 J/kg.K at 20°C (Laurent et al., 1984, Laurent, 1986, Goodhew et al., 2000, Goodhew and Allbrook, 2005, Hutcheon and Ball, 1949, Hill, 1993, Delgado and Guerrero, 2006, Wessling, 1974, Volhard, 2008, NF EN 1745 :2002).

For an earth-straw composite, x being the amount of straw, the heat capacity is :

$$c = (1-x).c_{earth} + x.c_{straw}$$

Similarly, the heat capacity of earth depends on its moisture content following a linear relationship:

$$C(\theta) = C_{dry} + \theta.C_w$$

with θ being the volumetric water content, and $C_w = 4.18E6$ J / m³. K.

In addition to the intrinsic heat capacity of the material, there is the contribution due to phase change of the water contained in the material: the evaporation of water causes cooling and the condensation causes warming. The energy exchanged represents the latent heat of vaporization of water, which is of about 2400 kJ/kg (Kimura, 1988).

5.2 Thermal conductivity

Thermal conductivity λ indicates the amount of heat (in W) that goes through an area of one sq meter/one meter thickness when its interior and exterior faces differ in temperature by one Kelvin. It is expressed in W/m.K. The lower λ is, the more the material is insulating. Materials with $\lambda < 0.065$ W/m.K are considered insulating.

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Earth is a porous, unsaturated material. Heat transfer is related to several mechanisms: conduction in the solid, liquid and gas phases, convection, radiation, evaporation / condensation. To define the conductivity in such a material is complex. Apparent conductivity is the value of conductivity reached by measure, which results from the combination of all the mechanisms mentioned above. The equivalent conductivity is the conductivity value of a homogeneous material equivalent to the considered material, which would have the same macroscopic thermal behavior.

ρ (kg/m3)	500	1000	1500	1800	2000	2200
λ (W/mK)	0.2	0.3	0.6	1	1.2	1.5

Tab. 2 – Mean values of thermal conductivity for earthen materials.

<table>
<tr><th>Property</th><th>Unit</th><th>Compacted earth</th><th>Mold earth</th><th>Fibred earth</th></tr>
<tr><td>Clay content</td><td>%</td><td>5 - 30</td><td>20 - 40</td><td></td></tr>
<tr><td>Plasticity index PI</td><td>%</td><td>5 - 30</td><td>15 - 35</td><td></td></tr>
<tr><td>Initial water content w_{ini}</td><td>%</td><td>5 - 15</td><td>15 - 35</td><td></td></tr>
<tr><td>Dry density ρ</td><td>kg/m^3</td><td>1600 - 2200
(1700 - 2200)</td><td>1200 - 2100
(1200 - 1700 for adobe)</td><td>300 - 1200
(600 - 800)</td></tr>
<tr><td>Ambient water content w</td><td>%</td><td colspan="3">0 - 5%</td></tr>
<tr><td>Drying shrinkage</td><td>%</td><td>1 - 3
(0.02 – 0.1 for CEBs, 0.1 - 0.2 for rammed earth)</td><td>1 - 20
(0.02 – 0.1 for adobe)</td><td>proche de 0</td></tr>
<tr><td>Water vapour resistance factor μ</td><td></td><td colspan="3">5 - 13</td></tr>
<tr><td>Young Modulus E</td><td>GPa</td><td colspan="2">1.0 - 5.5
(0.7 à 7.0 for cement stabilized earth)</td><td>< 1.0</td></tr>
<tr><td>Uniaxial compressive strength Rc</td><td>MPa</td><td>0.4 - 3.0
(2.0)</td><td>0.4 - 5.0</td><td></td></tr>
<tr><td>Tensile strength Rt</td><td>MPa</td><td colspan="3">0.1 - 0.5
(0.5 - 1.0 for rammed earth and CEBs)</td></tr>
<tr><td>Massic thermal capacity c</td><td>J/kg.K</td><td colspan="3">600 - 1000
(~ 850)</td></tr>
<tr><td>Volumic thermal capacity C</td><td>kJ/m^3.K</td><td>960 - 2200</td><td>720 - 2100</td><td>180 - 1200</td></tr>
<tr><td>Thermal conductivity λ</td><td>W/m.K</td><td>0,5 - 1,7
(0,81 - 0,93)</td><td>0,3 - 1,5
(0,46 - 0,81)</td><td>0,1 - 0,3
(0,1 - 0,45)</td></tr>
</table>

Tab. 3 – Synthesis of the main properties of earthen materials for construction.

The thermal conductivity of dry earth depends primarily on its density and porosity. It varies between 1.5 W/m.K for dense earth (2200 kg/m3), and can drop to 0.10 W/m.K for mixtures of earth and hemp or earth and straw (500 kg/m3). Average values for several densities are shown in Table 2 (Boussaid et al., 2001, CSTB, 2007, Goodhew et al., 2000, Goodhew and Griffiths, 2005, Kleespies, 1994, Hutcheon, 1949, Laurent et al., 1984, Laurent, 1987, Maniatidis et al., 2007, Ola, 1987, Wibart, 2010).

Conductivity increases with water content. For earth of about 1800 kg/m3 and suitable for rammed earth construction, it can vary from 1 to 1.2 W/m.K when the water content varies from 0 to 2%. For the same difference in moisture content, the change in conductivity can be more or less strong depending on the type of soil: not all earths have the same sensitivity to water. Earth by itself is not a good insulator, but when mixed with plant fibers and with a sufficient thickness, it can be used for the insulation of a building.

6 CONCLUSIONS

In conclusion from this overview, there is little reliable experimental data on the properties of raw earth for construction. This data is very fragmented as it often deals with one type of earth and focuses on only a few properties.

The main properties of raw earth updated through this review are summarized in Table 3 for the three main types of earth implementation for construction: compacted earth, mold earth and earth with added fibres. The values given in the reference (Houben and Guillaud, 1989) are recalled in parentheses for comparison.

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